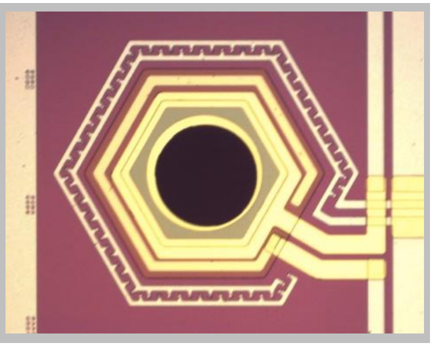

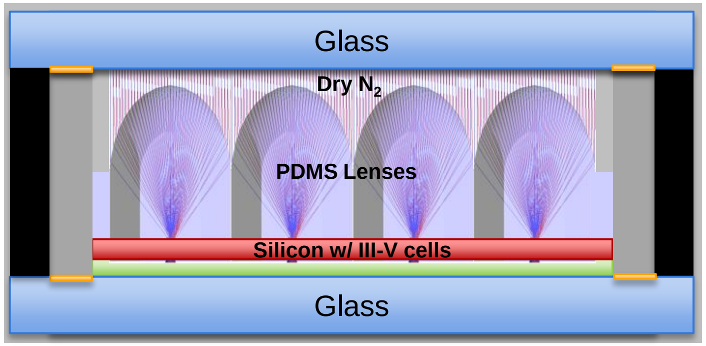

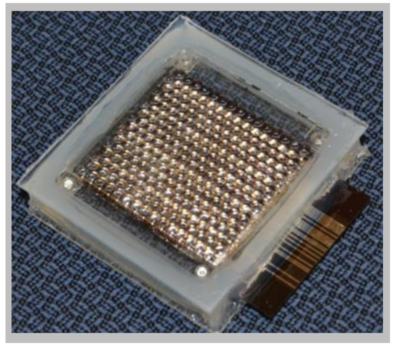

Exploiting Scale Effects in Photovoltaic Cells, Modules, and Systems

Gregory N. Nielson
Sandia National Laboratories

May 8, 2014

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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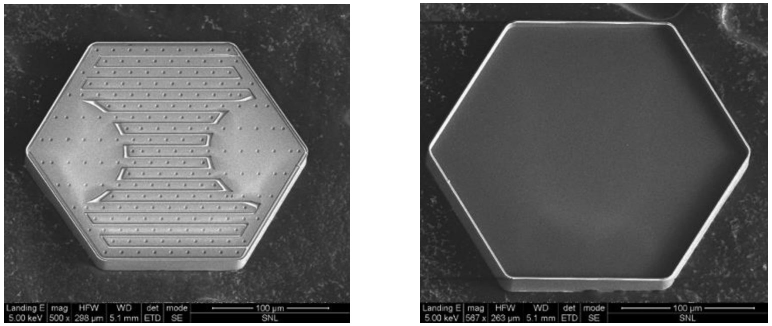
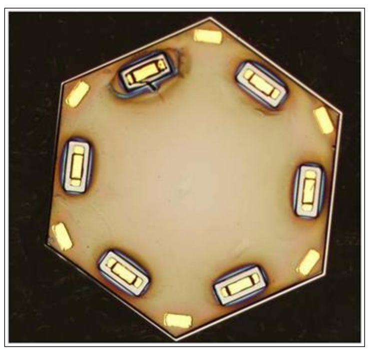
Microscale Photovoltaic Cells



Fully backside contacted c-Si solar cell showing contacts on back and unshaded front (“Sunny”) side of the cell



Fully back contacted 6 micron thick InGaP/GaAs dual junction cell with levelized back contacts

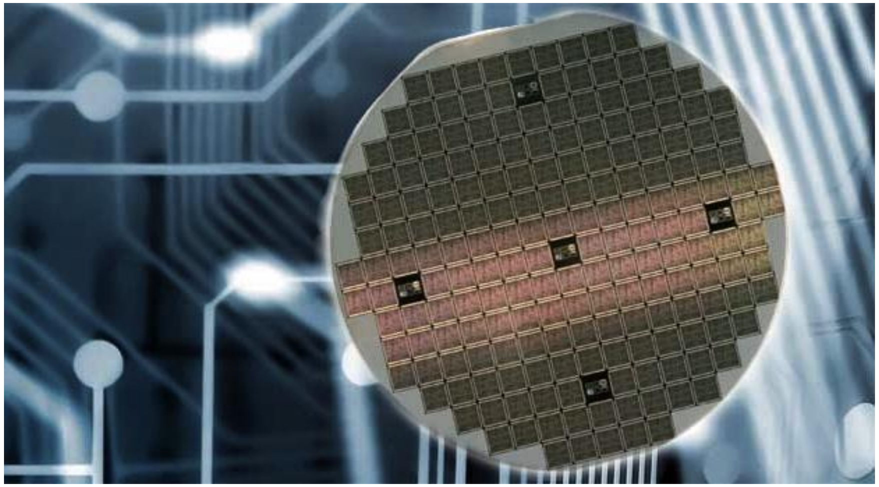
- Begin with materials that are well-known and can produce high efficiency without “something amazing happens here” roadmap steps
- Focus on demonstrating manufacturing techniques to achieve cells/modules/systems rather than on optimizing cell performance (let the experts do that part)
- Minimize the amount of semiconductor material used
- Develop fabrication techniques that allow wafer reuse
- Use 3D integration to create multijunction cells by combining silicon with III-V materials

- J. L. Cruz-Campa, M. Okandan, P. J. Resnick, P. Clews, T. Pluym, R. K. Grubbs, V. P. Gupta, D. Zubia, and G. N. Nielson, “Microsystem enabled photovoltaics: 14.9% efficient 14 μm thick crystalline silicon solar cell,” *Solar Energy Materials and Solar Cells*, **95**(2), 551-558 (2011).
- J. L. Cruz-Campa, G. N. Nielson, P. J. Resnick, C. A. Sanchez, P. J. Clews, M. Okandan, T. Friedmann, V. Gupta, “Ultrathin flexible crystalline silicon: microsystems enabled photovoltaics,” IEEE Journal of Photovoltaics, DOI: 10.1109/JPHOTOV.2011.2162973 (2011).

Microsystem Enabled Photovoltaics (MEPV)

Leverage concepts and technologies from existing successful microsystem industries (IC, MEMS, LED, LCD, etc.):

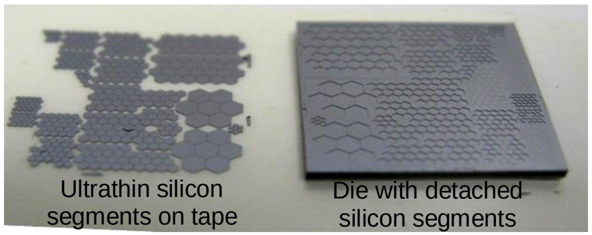
- Take advantage of beneficial scaling effects
  - Improved performance
  - Reduced cost
  - New functionality
- Parallel vs. serial manufacturing
- Increased integration - system vs. cell (component) paradigm
- Utilize established manufacturing supply chain and infrastructure (reducing CapEx)



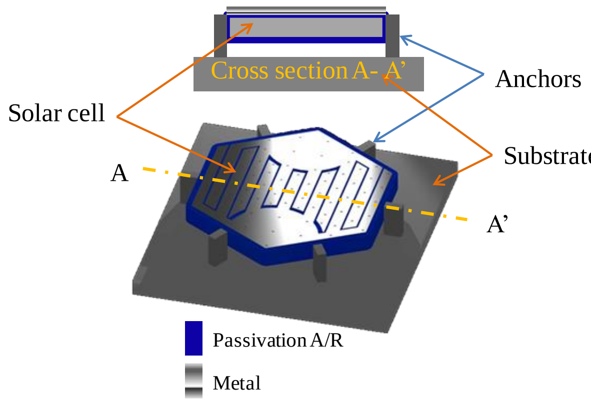
- *Integrated Circuit Market Size: $300B*
- *LCD Market Size: $102B*
- *LED Market Size: $12.5B*
- *MEMS Market Size: $10B*
- *Flat Plate PV Panel Market Size: ~$30B*

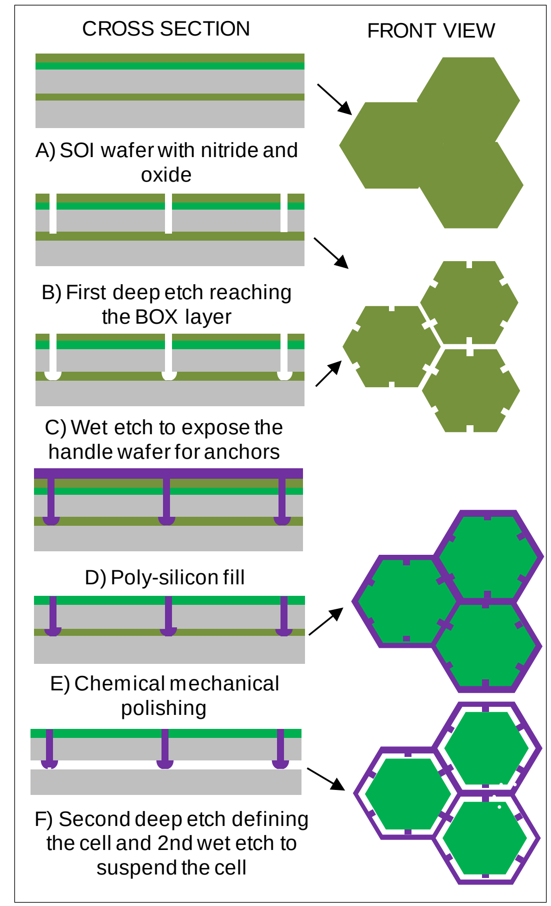
Tethered C-Si Solar Cells

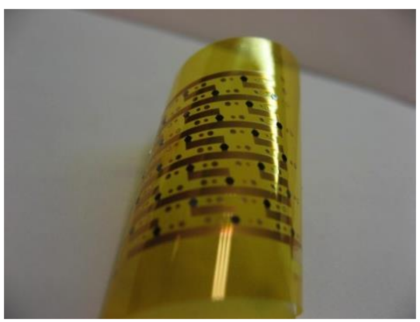
Concept of Suspended Cell



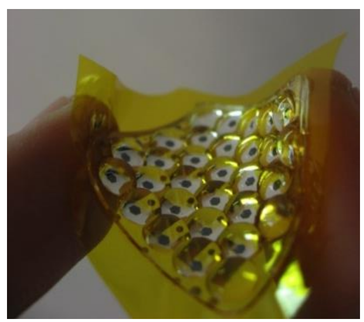
Released die can be transferred directly to a receiving substrate or to tape for standard pick-and-place assembly







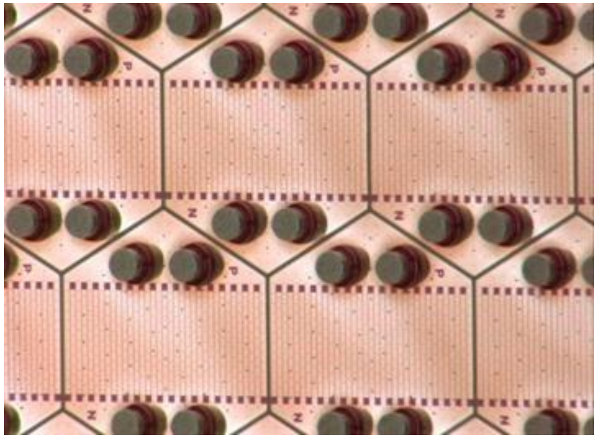
Electrically connected sparse array of 20 μm thick c-Si cells on 12 μm thick flex-circuit substrate.



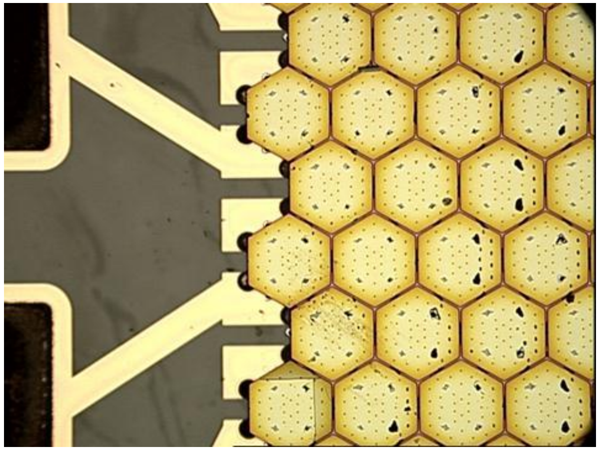
Sparse array (49X) with molded PDMS microlenses. (Note: mechanical demo only – optical system is not accurate.)

Jose L. Cruz-Campa, Gregory N. Nielson, Paul J. Resnick, Carlos A. Sanchez, Peggy J. Clews, Tom Friedmann, Murat Okandan, Vipin Gupta, *Ultrathin Flexible Crystalline Silicon: Microsystems Enabled Photovoltaics*, Invited talk to be presented at Photovoltaic Specialist Conference in Seattle, WA on June 23th, 2011

Silicon Cell Assembly and Flexible Module Results

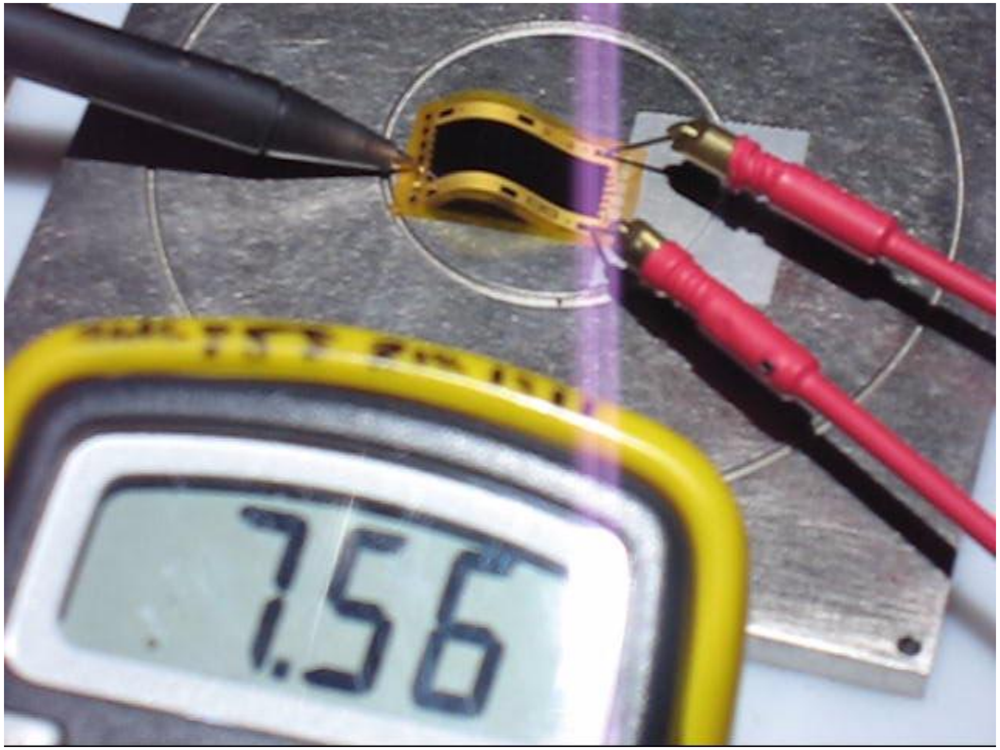


Cells on wafer with solder bumps

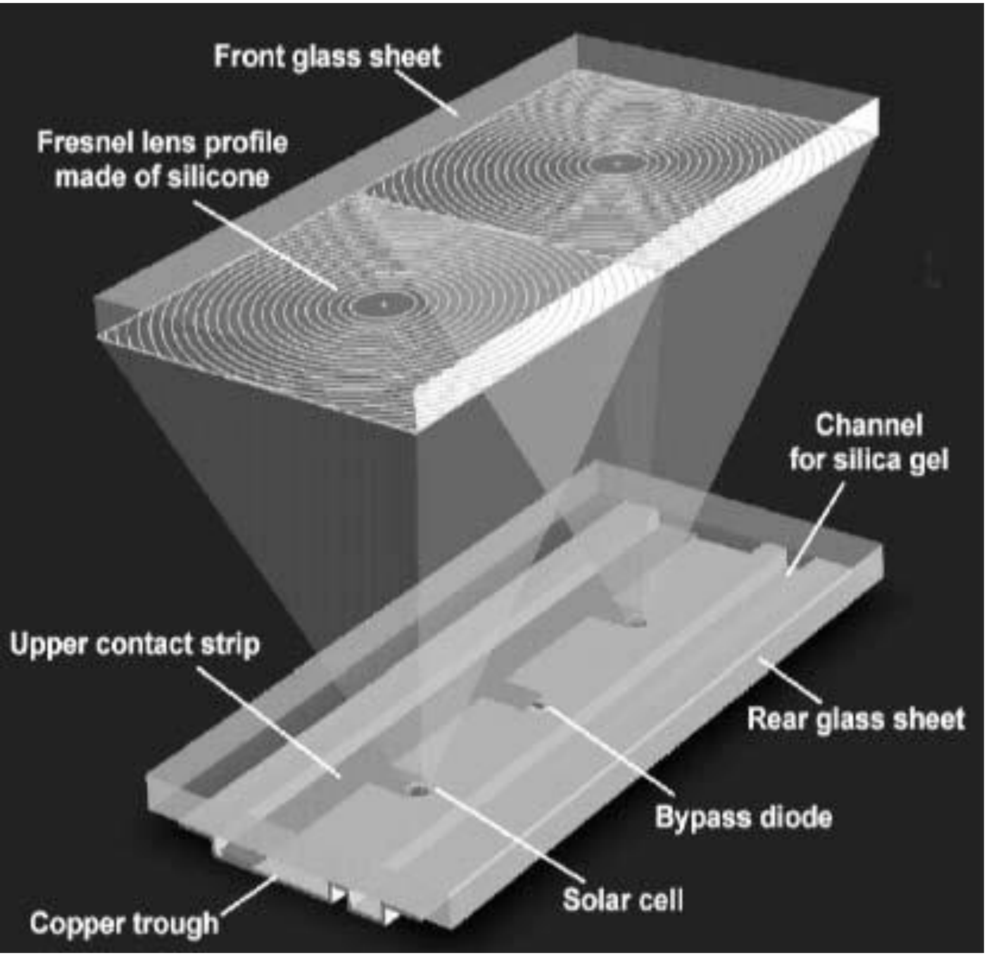


Cells after solder reflow connection to receiving substrate and removal from wafer

- Large array of ~500 cells on wafer assembled and interconnected in one step with industry standard solder bumps.
- MEPV module on flex material demonstrated a module efficiency of 14%. (only other PV technology (organic) that has similar flexibility is ~2%).
- 440 W/kg demonstrated (compared to current flex PV at 20-40 W/kg)
- 100 W system could be fit in a 1 foot long, 0.6 in diameter roll that weighs < 9 ounces (assumes 20% efficiency).



Concentrated Photovoltaic Systems (CPV)



Typical structure of a CPV module

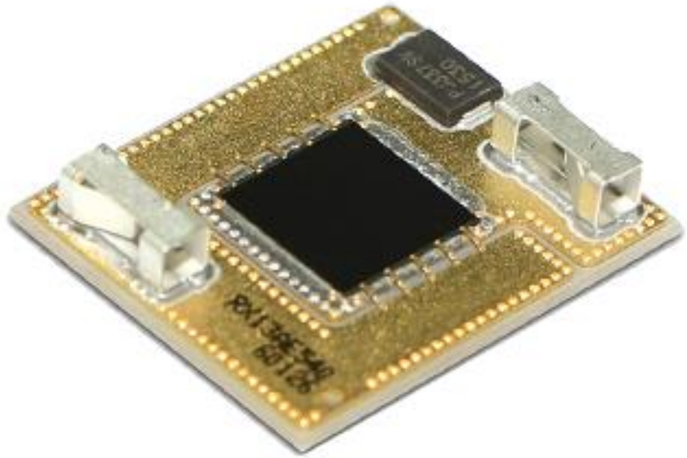
Suncore Plant (adjacent to SNL)

SOITEC

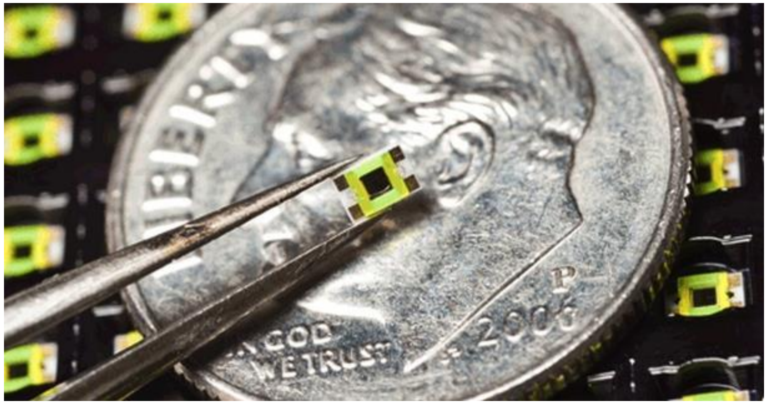
Amonix, 35.9% Record Module

Semprius

Concentrating Receivers and Heatsinks



SunCore Reciever



Semprius Reciever

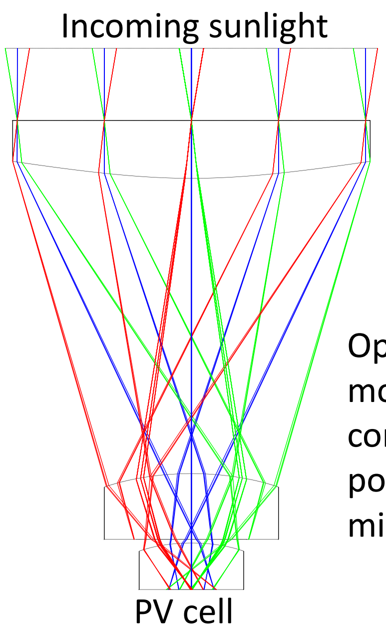
Heatsinks on Suncore Module

- Traditional CPV Receiver:
  - Bypass protection diode
  - Thermal management
  - Power conditioning electronics
  - Front and back cell contacts
  - High stability mechanics

Microlens Concentrator System

Sandia National Laboratories

- Very small cell sizes allow high-quality refractive optics to be molded inexpensively in microlens arrays
- Flat plate form factors (~1 cm module thickness)
  - Take advantage of BOS cost reductions resulting from flat plate PV industry
  - Utilize low-cost, flat plate 2-axis tracking systems
  - Suitable for commercial and utility installations
- More sophisticated optical designs are possible
  - $\pm$ 1.5° acceptance angle is minimum for low-cost, flat plate trackers (larger gives installation tolerance)
  - Up to 600X concentration

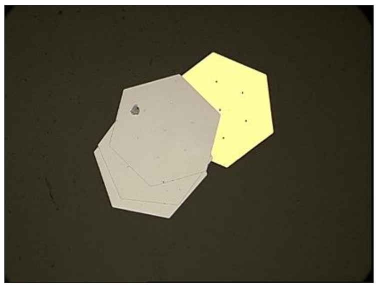


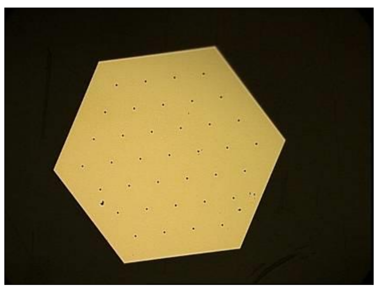
Optical ray trace model of optical concentrator made possible by microscale solar cells.

Low-cost, coarse 2-axis flat plate tracking

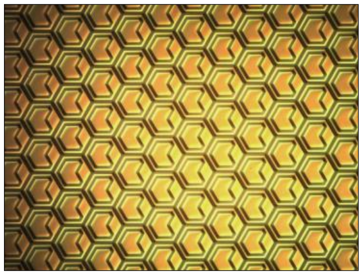
Microscale III-V PV Cells

- **Small area ELO**
  - Release time is relatively rapid (as quick as 10 minutes).
  - All backside (or frontside) contacting possible with small PV cells.

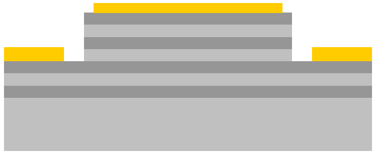




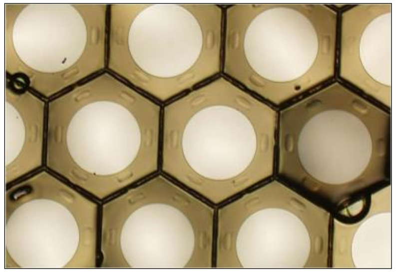
Single junction with front-back contacts



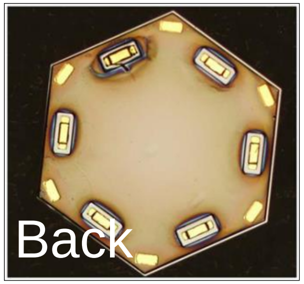
Back



Single junction with all back contacts at different levels



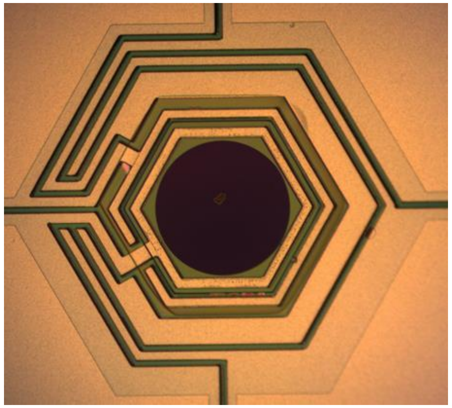
Front



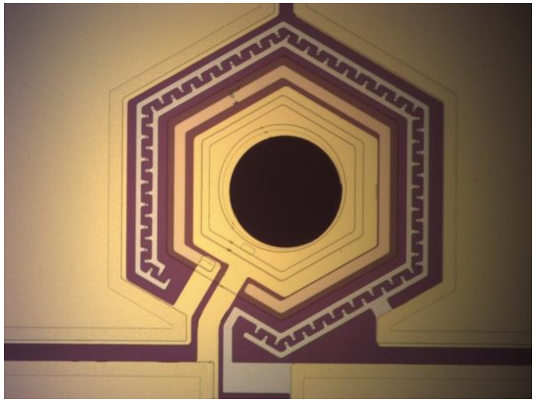
Cross section

Double junction with all back contacts at the same level

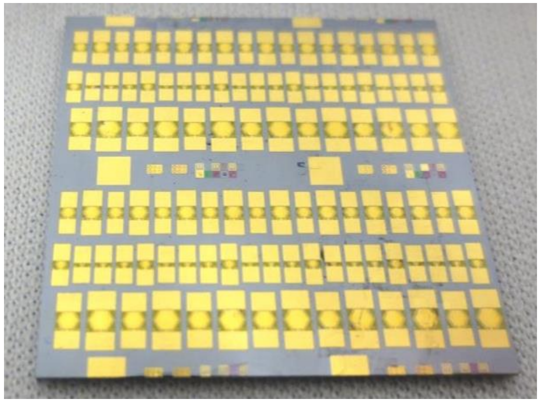
3D Integration of Multi-Junction Cells



Single junction GaAs on inactive silicon



InGaP/GaAs dual junction cell on active c-Si cell



InGaAs cell integrated on the backside of a silicon die

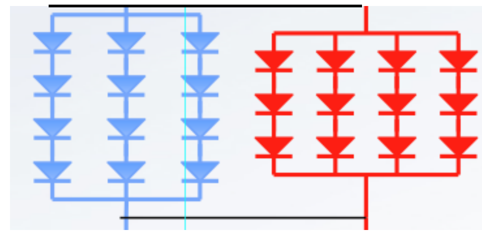
Material	**InGaN**	**InGaP**	**GaAs**	**Si**	**InGaAsP**	**InGaAs**
Bandgap	2.5	1.85	1.42	1.1	0.95	0.75

6 junction cell @ 50X ideal efficiency is > 60%

Lentine, A. L., et al., "Optimal cell connections for improved shading, reliability, and spectral performance of microsystem enabled photovoltaic (MEPV) modules," *Proc. 35th IEEE Photovoltaic Specialists Conference (PVSC)*, 003048-003054 (2010).

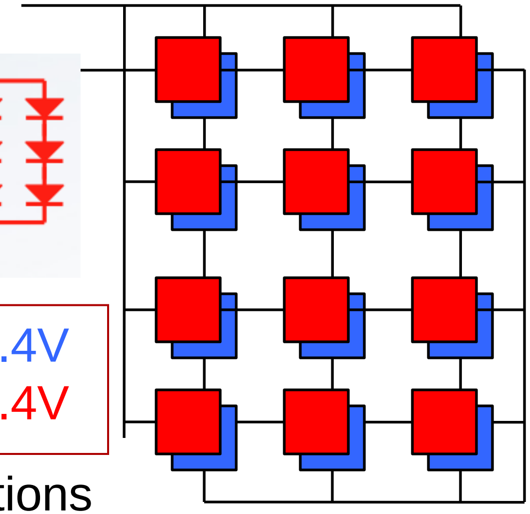
Voltage-matched Heterogeneous Multi-junction MEPV Modules

- *Freedom from current and lattice matching*
- *Better performance across spectra*
- *Rich connections for improved <u>system</u> reliability*

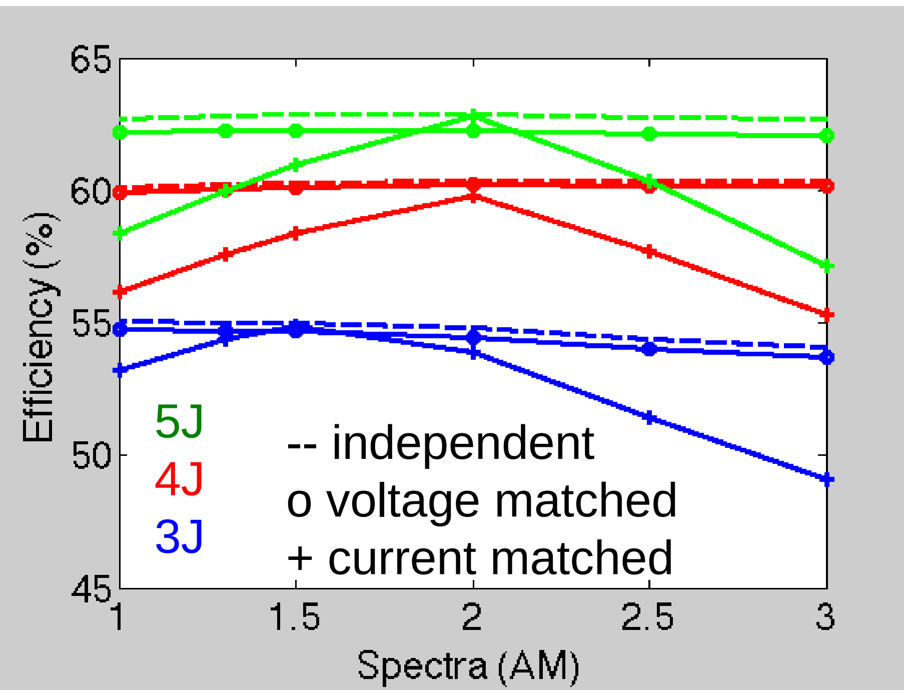


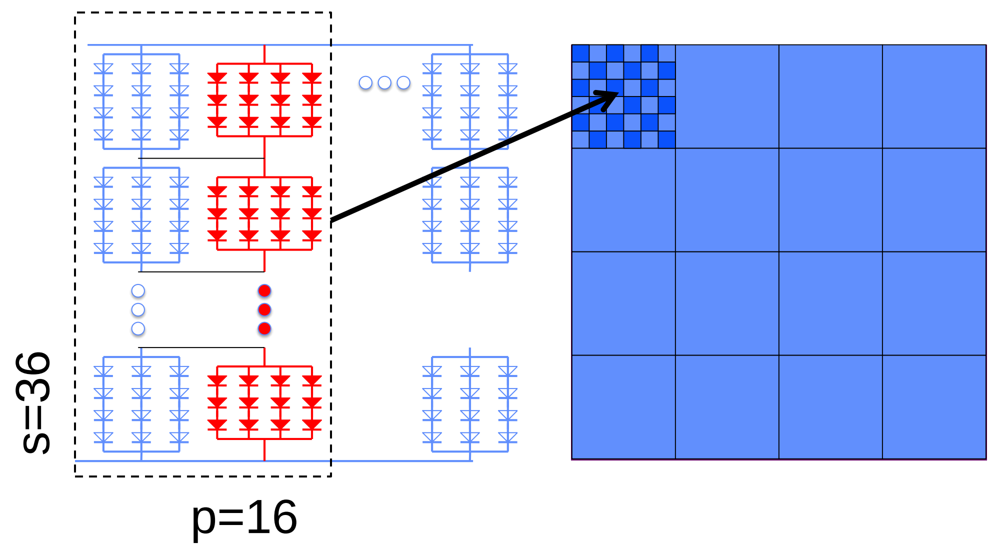
4 x 0.6V cells = 2.4V
3 x 0.8V cells = 2.4V

Logical Connections



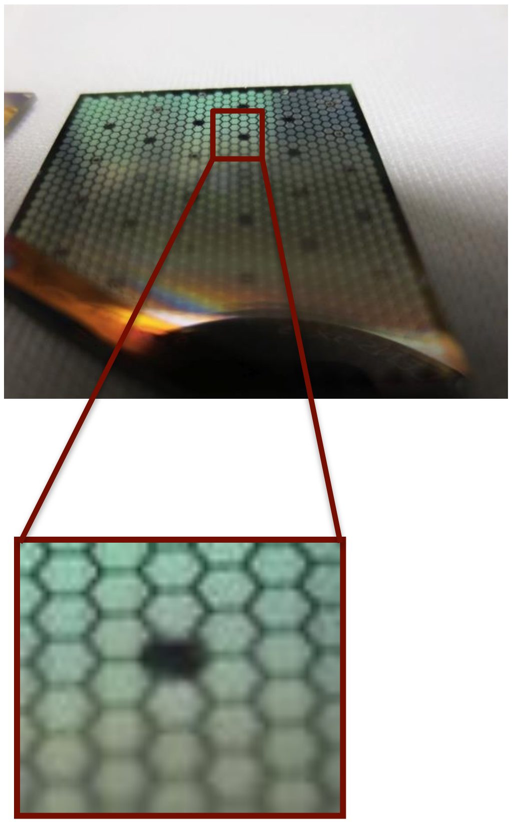
Physical Layout



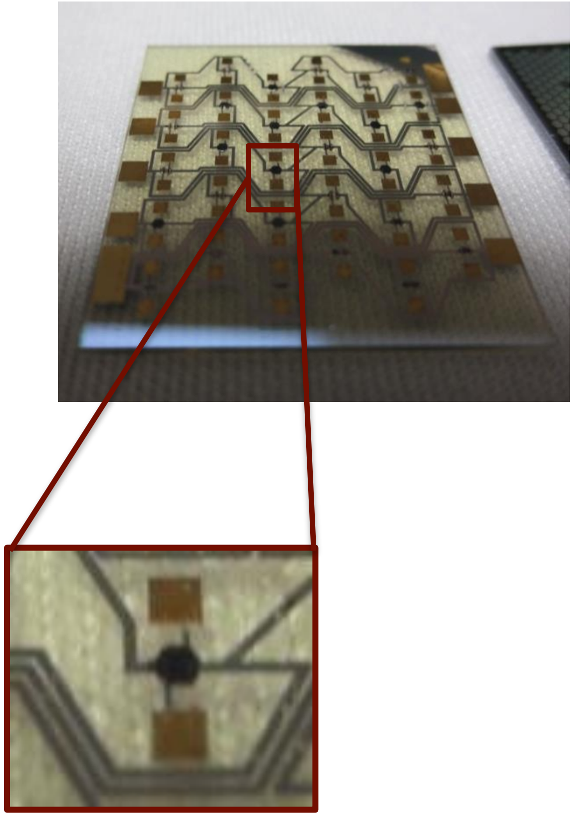


Sparse Cell Array Assembly

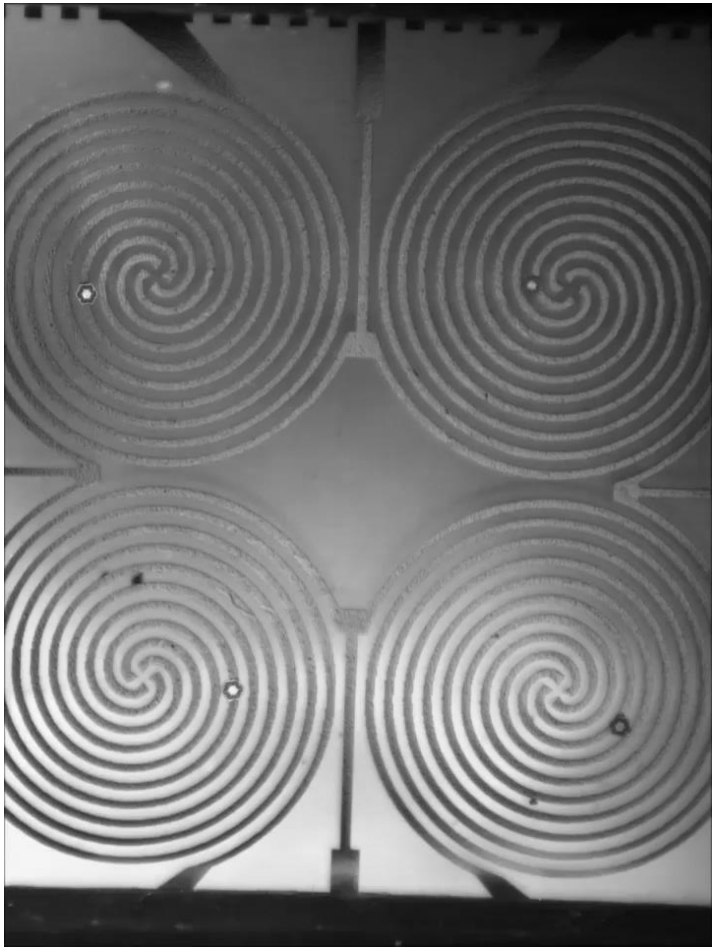
Donor Solar Cells from 1” x 1” die



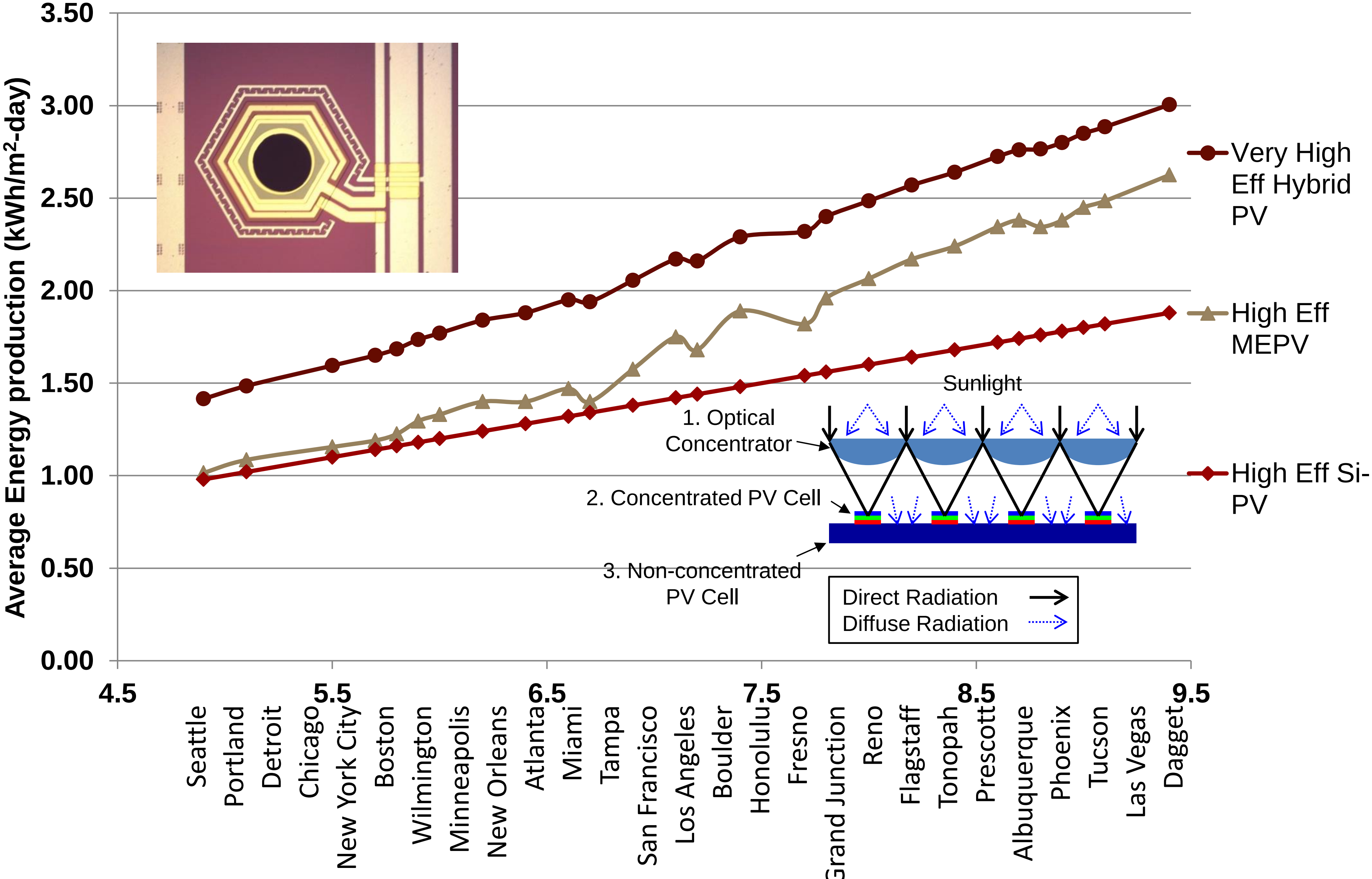
Glass substrate with cells transferred to interconnect circuit



MEPV cell directed self-assembly (Xerox-PARC)



1-Sun + Concentrated Hybrid PV System

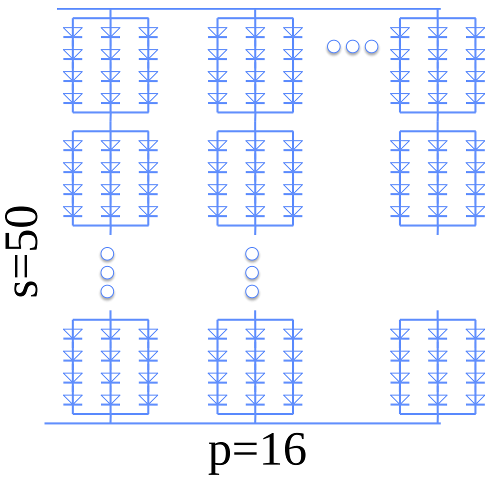


Annual Average Global Solar Radiation on a 2-axis tracking system per day (kWh/m²-day)

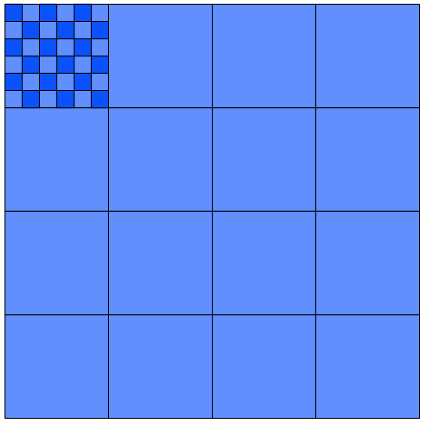
MEPV Interconnect Network

Due to the 10k-100k cells per sq. meter, new interconnect options become available that provide significant improvements over conventional cell strings

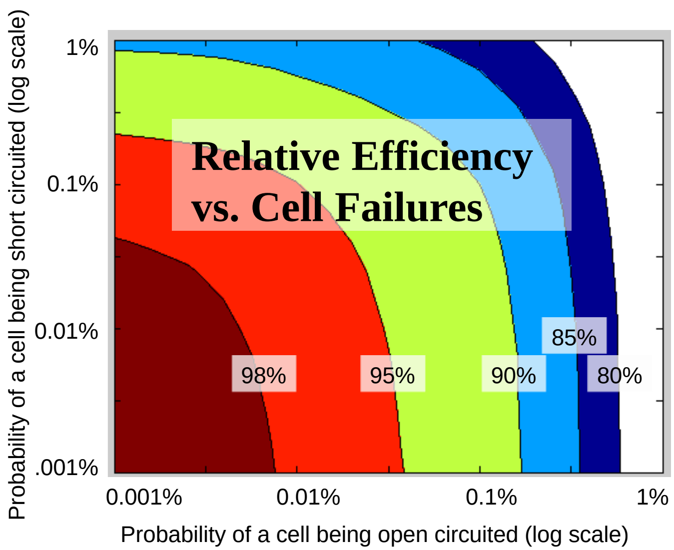
- Direct high voltage operation
- Better shading performance
- Tolerance to cell failures and variations
- New integrated inverter architectures reduce or eliminate discrete capacitors/inductors
- Allows voltage matching with independent junction connections



Logical Connections

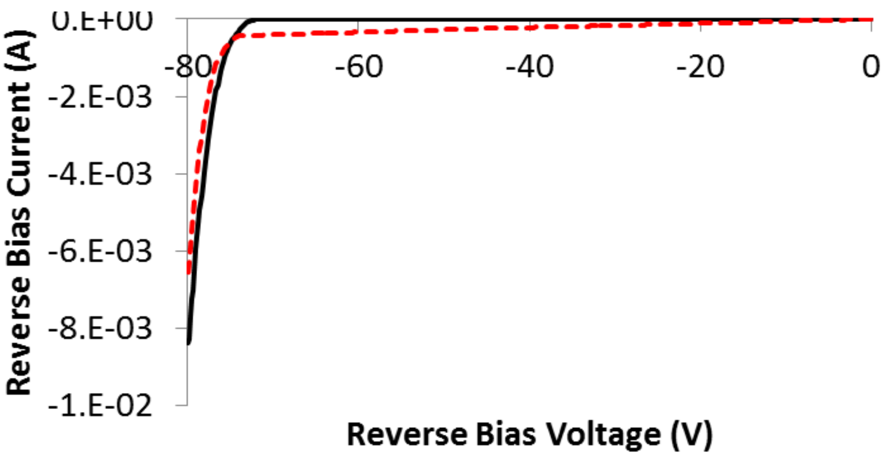


Physical Layout

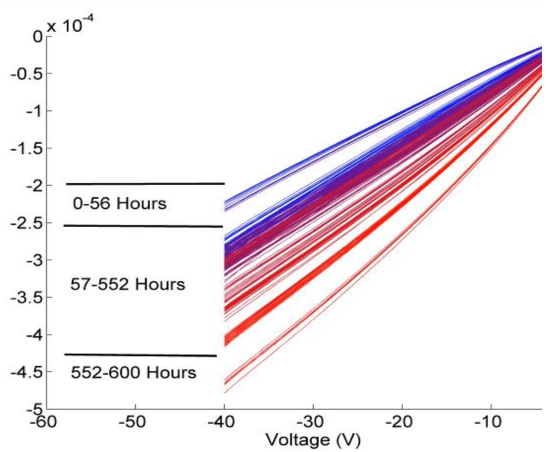


Johnson, B., et al., “A single-stage three-phase AC module for high-voltage photovoltaics,” *Proc. 27th IEEE APEC*, 885-891, (2012).
Lentine, A. L., et al., “Optimal cell connections for improved shading, reliability, and spectral performance of microsystem enabled photovoltaic (MEPV) modules,” *Proc. 35th IEEE PVSC*, 003048-003054 (2010).

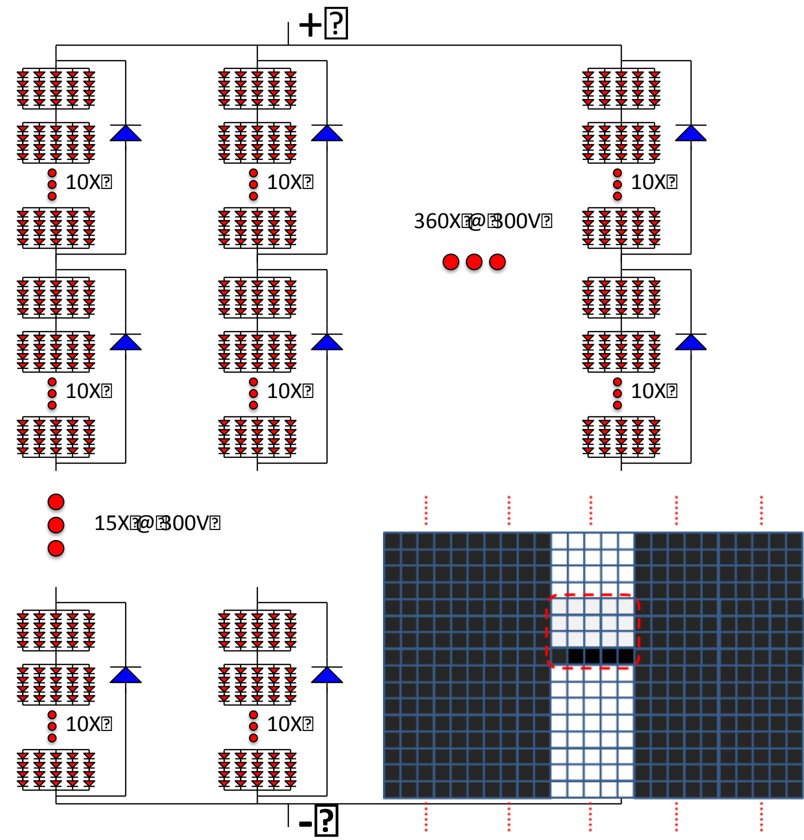
Multi-tiered cell protection strategy



1. Modules never approach breakdown voltage



2. Small currents cause little cell degradation in breakdown

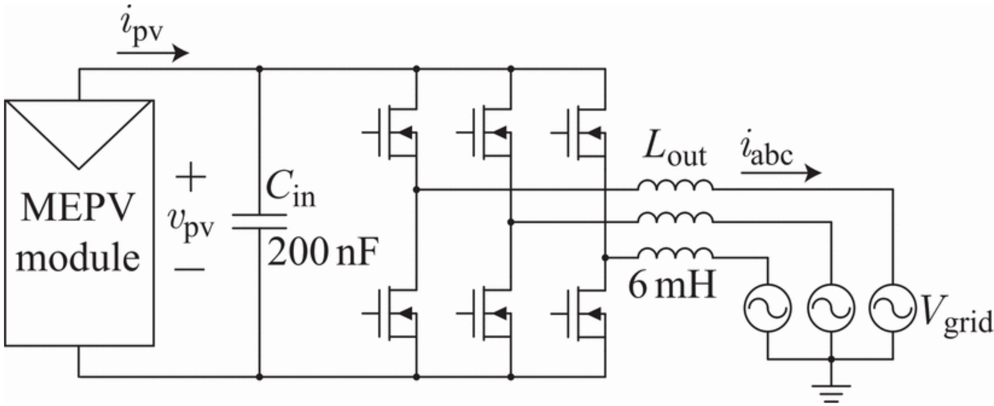


3. Rich series parallel connections lead to high voltages only with rare shading patterns

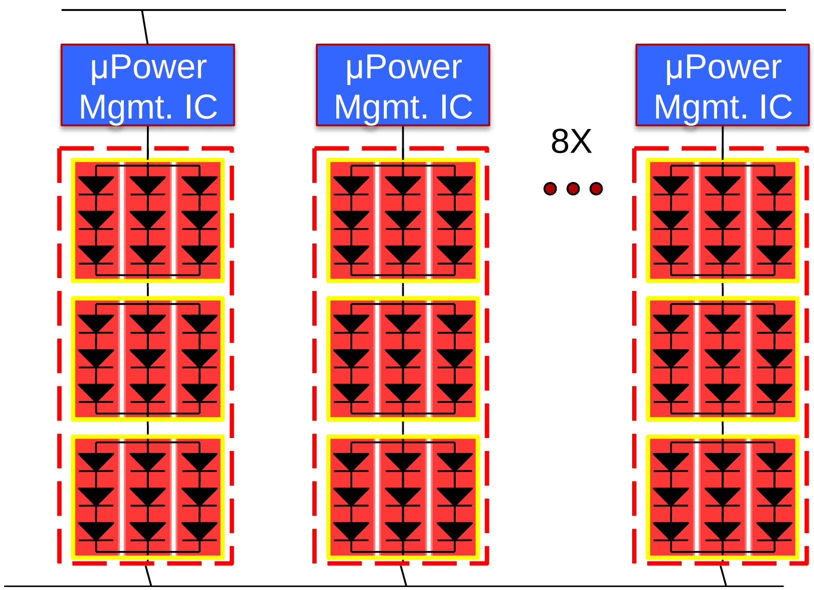
4. 1:N protection using cells as bypass diode; a group

System Level Benefits of MEPV

- DC/DC up converters not necessary due to ability to put out high voltage directly
- High voltages eliminate boost stages in inverters
- Integrated three phase inverters possible
  - No voltage up converters needed
  - Three-phase eliminates need for energy storage going from DC to AC
  - High-voltage within a small fractional module area makes interleaving of multiple invertor circuits possible which eliminates the need for low-pass filtering
- Integrated health monitoring
- Variable voltage output

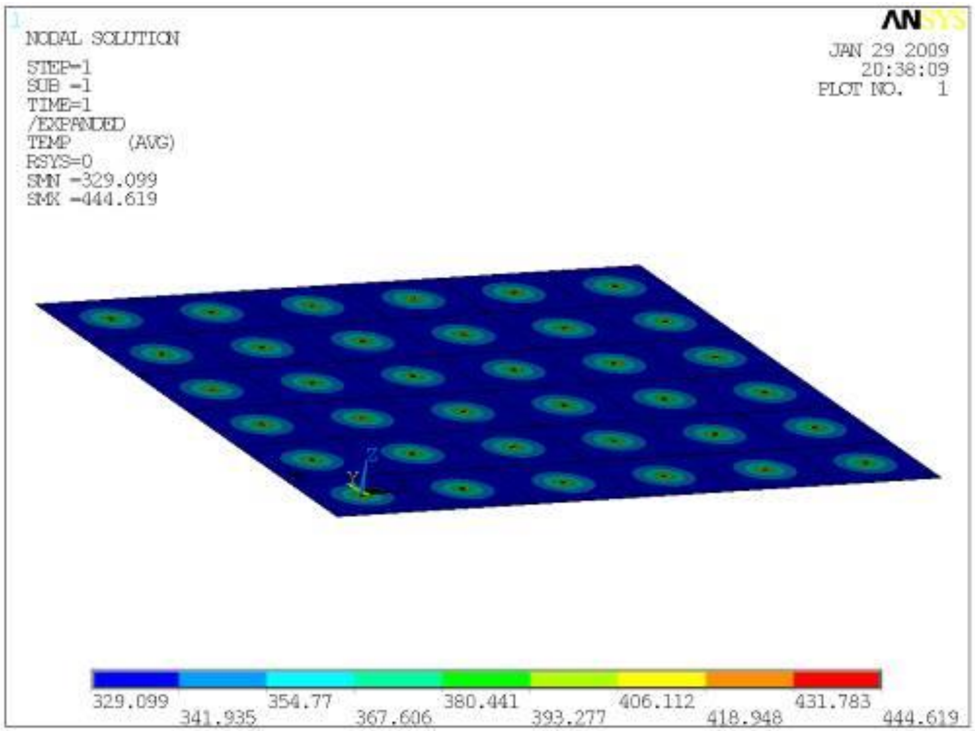


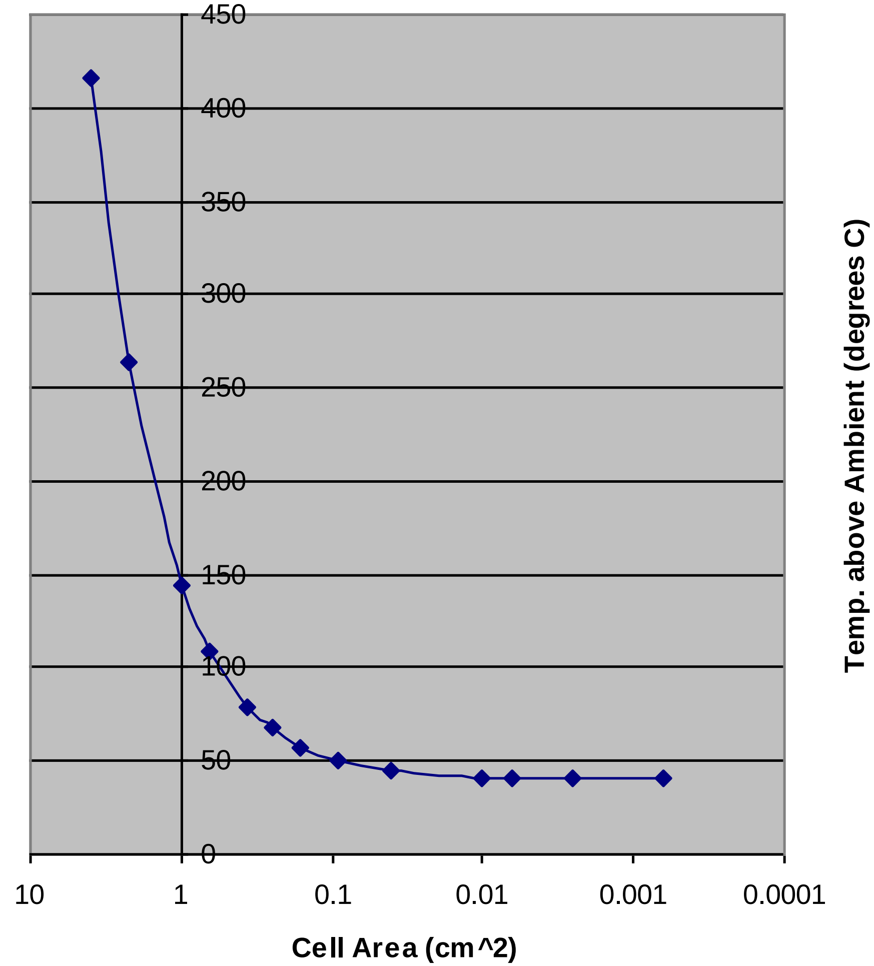
B. Johnson et. al. APEC 2012



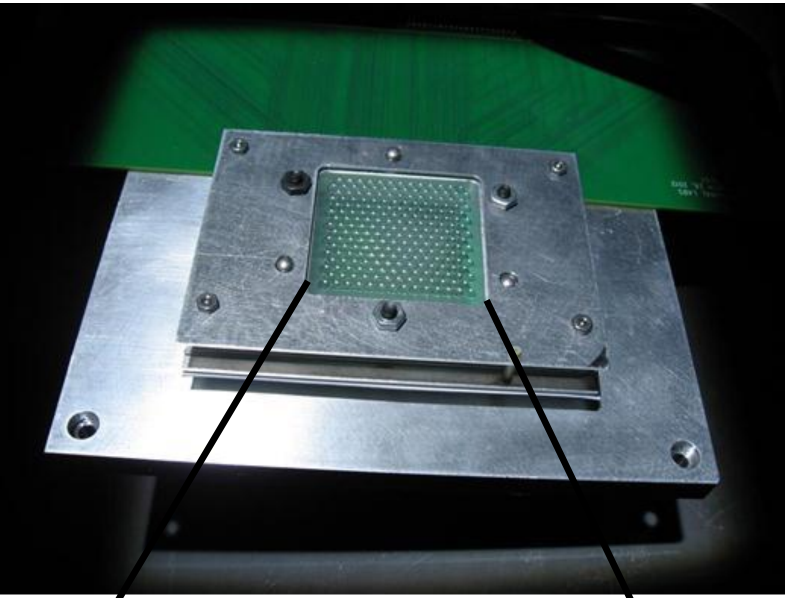
Thermal Performance of Small CPV Cells

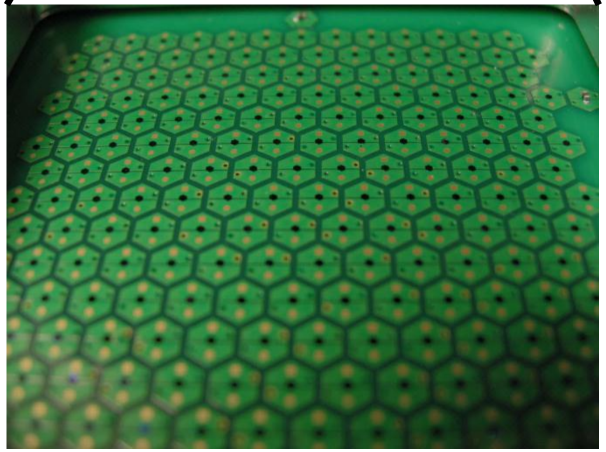
FEA analysis of a 500X concentrator system with cooling provided only by convection on module surface. As cell size decreases, the cell operating temperature converges to that of a one-sun module.



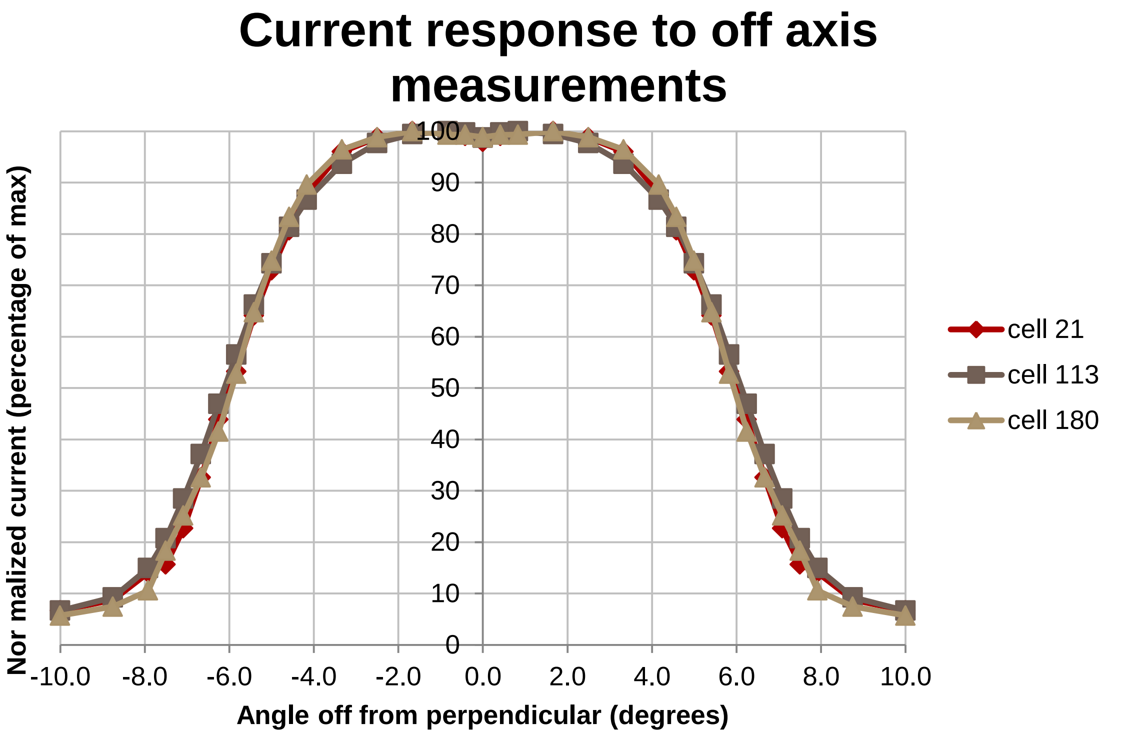


1^{st} Generation Microconcentrator



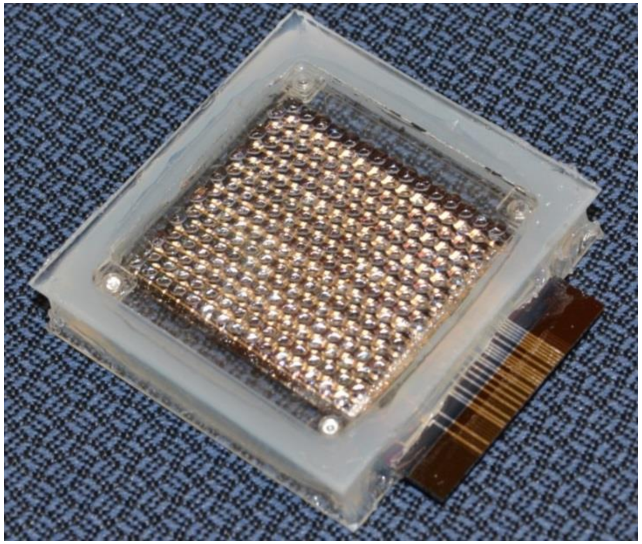


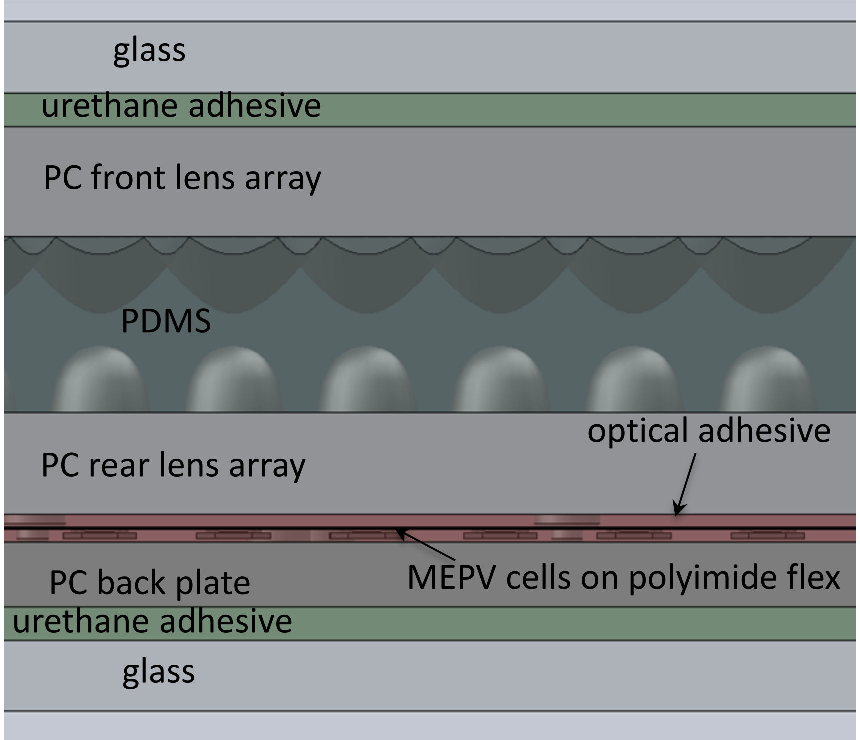
- 216 cells, microlenses
- $\pm 4^{\circ}$ degree acceptance angle (within 90% of peak power)
- 1.3 cm focal length
- 36X Concentration
- 3 lens stack



2nd Microconcentrator Prototype

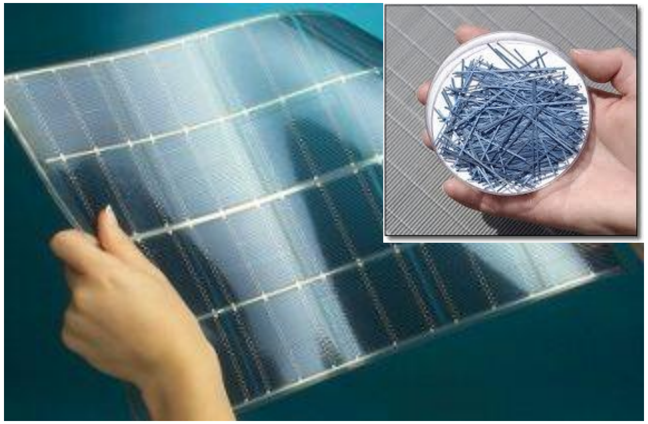
- Hexagonal closed pack array
  - 240 cell array (15 x 16)
  - 2x2 in footprint
- 2 plano-convex PC lens w/PDMS fill
  - 100x magnification, ±2.5° FOV
  - >90% transmission





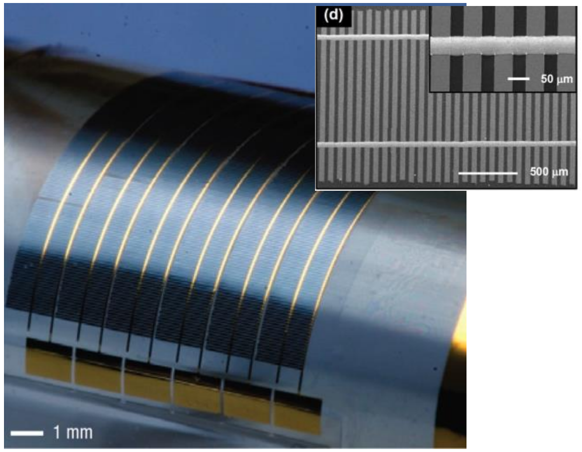
Other Microscale Photovoltaic Efforts

Sandia National Laboratories



Sliver Cells™
UNSW/Origin Energy

M. J. Stocks, et al., "65-micron thin monocrystalline silicon solar cell technology allowing 12-fold reduction in silicon usage," 3rd World Conference on Photovoltaic Energy Conversion," May 2003.

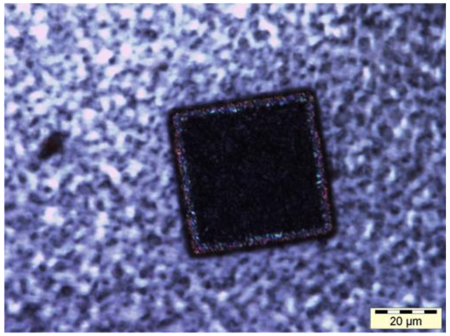


University of Illinois

J. Yoon, et al., "Ultrathin silicon solar microcells for semitransparent, mechanically flexible and microconcentrator module designs," *Nature Materials*, **7**, Nov. 2008.

Semprius/University of Illinois

C. A. Bower, et al., "Transfer Printing: An approach for massively parallel assembly of microscale devices," IEEE Electronic Components and Technology Conference, 2008.



M. Paire, et al., "Toward microscale Cu(In,Ga)Se_2 solar cells for efficient conversion and optimized material usage: Theoretical evaluation," *Journal of Applied Physics*, **108**, 2010.

MEPV Affordability:
System leverages PV infrastructure

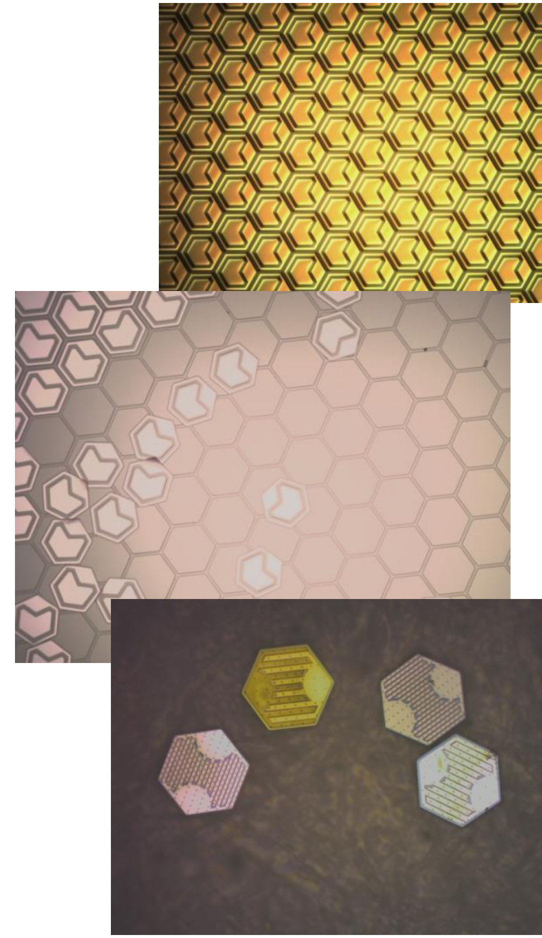
$$\text{LCOE}=\frac{\text{NPV}\left[\text{Module Cost}+\boxed{\text{BOS Cost}+\text{Tracker Cost}+\text{Installation Cost}+\text{O\&M Cost}}\right]}{\text{NPV}\left[\text{Energy generation}\right]}$$

LCOE Component	PV	CPV	MEPV	MEPV Comments
Module Cost	Low	High	TBD	Under development
BOS Cost	Low	Low	Low	Costs are the same as or lower than one-sun Si PV
Tracker Cost	Low	High	Low	
Installation Cost	Low	High	Low	
O&M Cost	Low	High	Low	
Energy Generation	Low	High	High	Similar to or higher than CPV, due to high-efficiency cells and optics

Conclusion and Acknowledgements

Conclusions

- Micro-scale solar cells allow improved performance and reduced costs across many CPV system components (modules, trackers, inverters, installation labor, wiring, etc.)
- Leveraging existing manufacturing infrastructure is possible and may be key prior to large volume production
- Leveraging advances in flat plate PV BOS costs may also be key to catching up to and supplanting flat plate PV



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